Temporal and Spatial PFC Temperature Profiles in KSTAR 2010

E. N. Bang, K.M. Kim, H.T. Kim, H.K. Kim, K.S. Lee, S.H. Hong, Y.M. Jeon, J.G. Bak, W.C. Kim and H.L. Yang
KSTAR Research Center
National Fusion Research Institute
bang14@nfri.re.kr

Y.S. Oh
Department of Electrical Eng. & Center for Edge Plasma
Hanyang University
Seoul, Korea

***Abstract*— In- and outboard Plasma Facing Components (PFCs) of KSTAR (Korea Superconducting Tokamak Advanced Reasearch) have been fully installed in 2010 for D shaped diverted plasmas. Before the start of plasma operation, the PFCs were baked up to 200 °C by hot nitrogen gas circulation system to remove impurities including water. The surface temperature of the PFC tiles was monitored by 200 thermo-couple sensors during the plasma operation (plasma shot or Glow Discharge Cleaning(GDC)), and the temporal and spatial (poloidal) temperature profiles are obtained. Depending on the heat flux on each tile, the surface temperature shows time-dependency. After 1-hour morning He GDC, the temperature of the PFCs at inboard side has reached at 40 °C. After an H-mode shot, the temperature of divertor tiles around the striking points was substantially increased. The time-averaged total heat flux after an specific H-mode in 2010 was estimated to be approximately 10kW/m^2.**

Keywords- Plasma Facing Component(PFC); PFC baking; heat flux, H-mode

I. Introduction

A large upgrade has been accomplished in KSTAR to achieve highly shaped diverted plasmas. Plasma Facing Components (PFCs) such as inboard and outboard limiters, divertors, and passive stabilizers were installed inside the vacuum vessel (VV)[1]. The divertor has been designed for single null(SN) and double-null (DN) operation modes, and the basic design requirement is that the actively water-cooled back-plate (or heat-sink plate) and the covering tiles that are made of carbon fiber composite(CFC) should accommodate 4.3MW/m^2 of heat flux. However, graphite is one of the excellent candidates for the divertor tiles owing to low heat flux and relatively short pulse in phase I of the KSTAR operation which will be terminated by end of 2012 [2]. In addition, baking and cooling (B&C) pipe systems for all PFCs were installed to fulfill baking and active cooling of PFCs. The PFCs are baked by circulating hot nitrogen gas through internal tubes of back-plates of the PFCs.

PFCs in a fusion reactor should be able to handle the high-energy flux which passes through the plasma boundary both during steady-state operations and also during transient events such as disruption and edge localized modes (ELMs) [3]. ELMs are a significant concern in tokamak plasma as they cause high, transient heat loads on the PFCs [4]. Heat loads to the surface in tokamak are usually derived using data from infrared (IR) cameras, Langmuir probe arrays or thermo-couples [5]. But those diagnostic systems are not yet installed, so that we attempted to calculate the heat load from change of temperature on PFC tiles.

In KSTAR, more than 200 pieces of thermo-couple (NiCr-Ni K type) were installed inside the graphite tiles at 5mm behind the surface [6]. During baking and plasma operation, the temperature of PFC tiles is monitored for machine safety every second.

In this paper we report the result of PFC baking and the comparison of the temperature measurements in L- and H-modes for heat load calculations

II. Plasma Facing Components

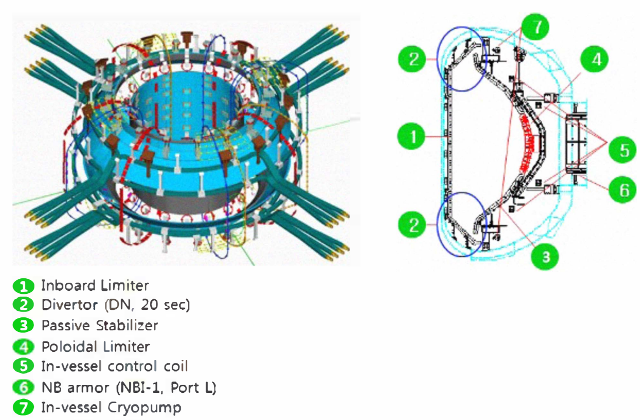

Figure 1. Configuration of the KSTAR PFCs

As shown in figure 1, PFCs of KSTAR were comprised of inboard limiter, divertor (which is divided into inboard, central and outboard divertors), passive stabilizer, poloidal limiter, and neutral beam (NB) protection armor system [1]. All back-plates of PFCs were made of SS 316LN and copper alloys (CuCrZr) on which graphite tiles are mechanically attached. The back-plates are actively cooled by circulating water at room temperature that flows through the grooved channels inside the back-plate. Especially, the coolant has been designed to remove heat influx up to 4.5MW/m^2 in the divertor region under steady state operations. In addition to the heat removal capability of

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the cooling system, the PFCs can be baked up to ~300℃ by circulating hot N_2 gas [7].

A. *PFC Temperature Monitoring*

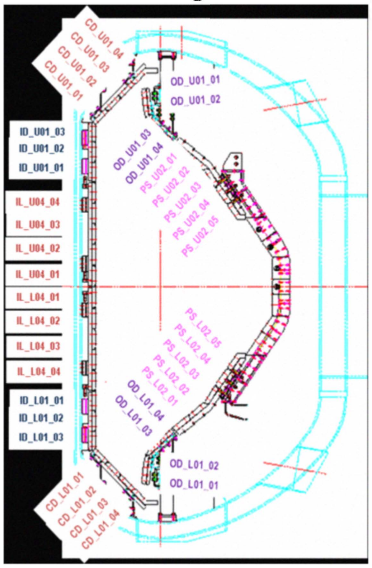

Figure 2. Location of temperature sensors

During the plasma operation, the temperature of PFCs was monitored by 200 sensors at different toroidal and poloidal positions. Figure 2 shows the location of thermo-couples for temperature measurement of the PFC tiles. In order to construct poloidal temperature profiles, several arrays of thermo-couples were chosen as shown in figure 2.

B. *PFC Baking*

Main purpose of the high-temperature baking is removal of impurities such as H_2, H_2O, CO, CO_2 from the surface of the PFC and VV. PFCs were baked up to 200℃ by circulating the nitrogen gas at 5 bar of gas pressure through internal holes or external tubes, while the VV was maintained at 120℃. As shown in figure 3, when the temperature of hot nitrogen gas supply was increased to 225℃, the surface temperature of the PFCs was increased from the room temperature to 200℃ in 6 days of baking operation. And the supply pressure of nitrogen gas was maintained at 5 bar. The rate of temperature increase was 3~5℃/h which has been determined to minimize mechanical stress on the VV and PFCs structure. While the temperature of nitrogen gas supply was increasing, the surface temperature of PFCs was uniformly controlled to keep temperature difference within 50℃ as shown in the figure 3. Then the pressure of vacuum vessel and partial pressure of M18 and M28 were monitored. After PFC baking was completed, the pressure decreased. Although the supplying pressure of nitrogen gas was raised to 5.0 bar, partial pressure of mass 28 amu (N_2 or CO) was maintained low within allowable value indicating no detectable nitrogen leakage from the PFCs B&C lines.

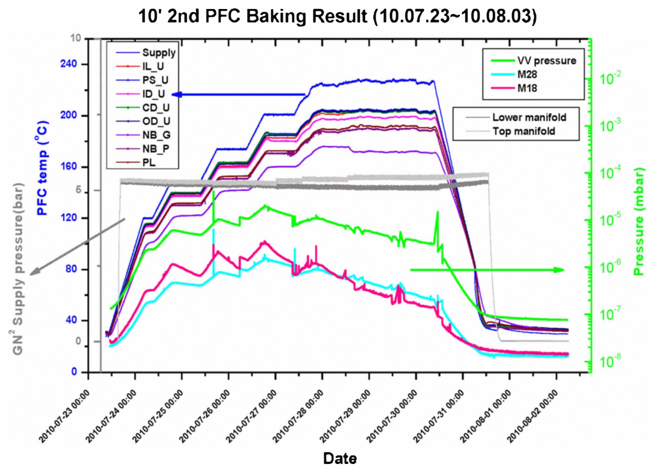

Figure 3. 10' 2nd PFC baking result

III. Temporal And Poloidal Temperature Profiles

A. *After GDC*

The wall conditioning of the KSTAR vacuum vessel has been performed in order to remove various kinds of impurities including H_2O, carbon and oxygen. The RF-assisted glow discharge cleaning (GDC) was carried out using D_2 or He. During the machine cool-down, the GDC was not performed. Figure 4 shows the temperature change before and after GDC. After 1-hour morning He GDC, the temperature increment of the PFCs at inboard side has reached up to 40 °C. It is because the GDC antenna is located at the center of the machine (r=1.8 m) at midi-plane. Since active cooling was not available in 2010 campaign, the PFCs were cooled down by thermal radiation.

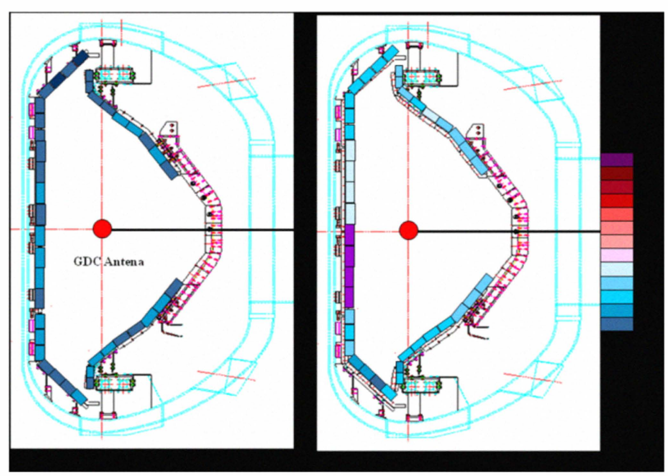

Figure 4. Change of temperature before and after GDC

B. *Heat flux of L- and H-mode*

KSTAR has achieved a plasma current up to 700kA and plasma duration up to 6.7 seconds and advanced the plasma performance to the H-mode in 2010 campaign. The H-mode, a baseline operation mode in ITER, is characterized by good confinement of plasma energy and particle caused by a transport barrier near the plasma edge and occurs when heating

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power is deposited in the core plasma above a threshold value [8].

After a plasma discharge, temperature of specific part was increased more than other parts as figure 5. The locations of temperature sensor are shown in figure 2. From the temperature profiles, we have calculated qualitatively heat load towards PFC tiles. Note that, this calculation is simple and rough estimation. Looking at temperature changes, temperature are rising after the end of discharge and the time to reach the highest temperature is different respectively. Then the highest temperature can be assumed that temperature of the whole, because of the high thermal conductivity of graphite tile, the slow response time of thermo-couple (about 2~3s) and the temperature sensors were installed in the graphite tiles at 5mm behind the surface.

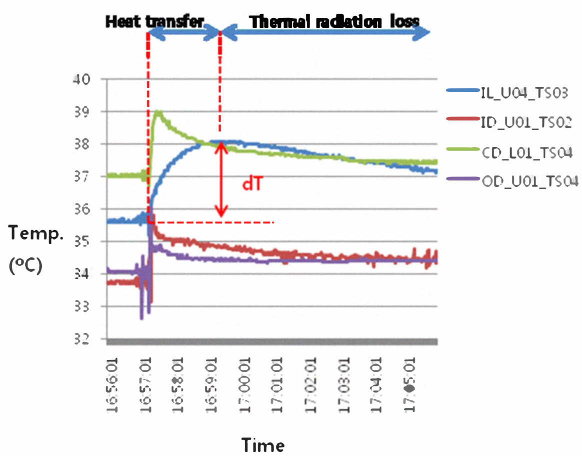

Figure 5. Temperature increase of a few tiles after 4333 shot

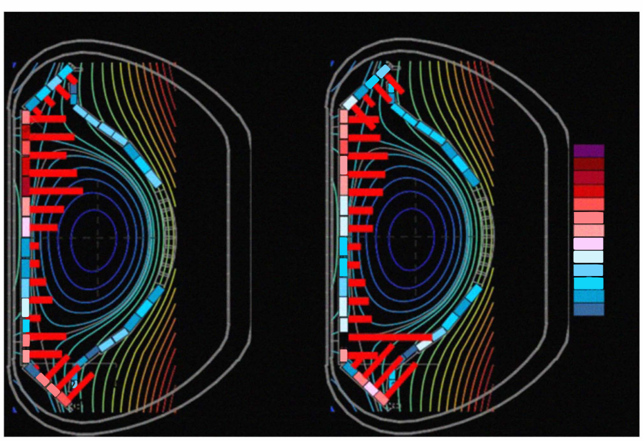

Figure 6. Temperature increase of PFC tile after L- and H-mode with results of EFIT calculation

- Choose several L- and H-mode discharges having similar pulse durations, I_p, heating power.
- Calculate the increase of each tile temperature for a poloidal section after discharge.
- Calculate the energy toward each tile.
- Heat load of a tile extend to total PFC tiles through.

$$Q\ (J) = mc\delta T \quad (1)$$

$$\text{Heat load(W)} = Q(J)/\text{Pulse durations(s)} \quad (2)$$

$$\text{Heat flux}(W/m^2) = \text{Heat load(W)}/\text{Surface area}(m^2) \quad (3)$$

TABLE I. HEAT LOAD OF L-MODE SHOT

Date	**10.11.16**		**10.11.18**
Shot Number	**4353**	**4354**	**4425**
Ip (kA)	613	624	621
Pulse > 0.1 kA (msec)	3265	3241	3213
Ohmic Energy(MJ)	1.51	1.51	1.55
ECH_Energy(MJ)	0.55	0.51	0.53
NBI_Energy (MJ)	4.22	4.19	3.55
Total Input_Energy(MJ)	6.28	6.21	5.63
Input Energy_Tile(MJ)	**5.09**	**5.04**	**4.57**
Heat Energy (MJ) _total tile volume	**1.9**	**2.0**	**1.9**
Heat Load (MW)	**0.58**	**0.62**	**0.59**
Heat Flux_everage(kW/m^2)	**10.39**	**11.02**	**10.56**

TABLE II. HEAT LOAD OF H-MODE SHOT

Date	**10.11.15**	**10.11.16**	
Shot Number	**4333**	**4362**	**4364**
Ip (kA)	623	616	615
Pulse > 0.1 kA (msec)	3326	3162	3175
Ohmic Energy(MJ)	1.60	1.47	1.46
ECH_Energy(MJ)	0.53	0.54	0.54
NBI_Energy (MJ)	3.69	2.34	2.35
Total Input_Energy(MJ)	5.82	4.35	4.35
Input Energy_Tile(MJ)	**4.72**	**3.53**	**3.53**
Heat Energy (MJ) _total volume	**2.0**	**1.8**	**1.7**
Heat Load (MW)	**0.60**	**0.57**	**0.54**
Heat Flux_everage(kW/m^2)	**10.74**	**10.17**	**9.56**

The heat flux after L- and H-modes discharges are approximately 10kW/m^2 and similar in both modes. This is due to the quick back-transition from H- to L-mode, so that the global temperature increase was very limited and couldn't contribute much. Since IR camera system for the temperature measurement is not installed in 2010, comparison is not possible.

C. Spatial Temperature Profile During H-mode Discharge

After accessing the H-mode in KSTAR, the temperature of divertor tiles was substantially increased around the striking points. Therefore, the temperatures of PFCs were analyzed for a poloidal section and compared with other calculation or diagnostics data. Figure 7 shows the temperature changes of tiles for a poloidal section after shot 4333 and the reconstructed flux contours from EFIT analysis. The right side of figure 7 is shown the total increase of temperature after the discharge and left side is shown the EFIT in the specific time. Although these cannot be accurately compare, the high temperature region on divertor is similar to the EFIT result. The poloidal distribution of ion saturation current j_{sat} is obtained from the Langmuir probe measurement at the lower divertor region for the H-mode discharge as shown in figure 8. Two peaks of j_{sat} are observed in the poloidal distribution, and their positions agree well with those of two strike points estimated from the EFIT reconstruction. Thus, higher particle flux can be expected at the PFC tiles near the strike points during plasma discharge because j_{sat} means particle flux from the plasma boundary to the Langmuir.

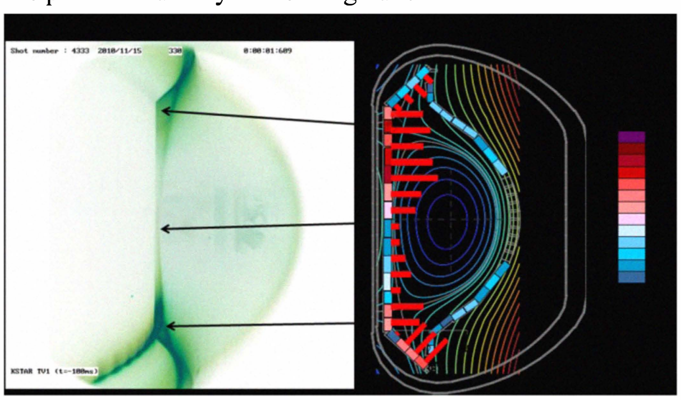

Figure 7. Change of temperature after shot 4333 and compare with result of EFIT calculation.

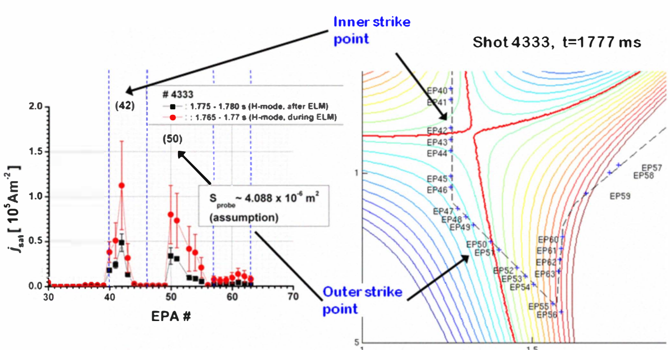

Figure 8. Results from fixed Langmuir probe array measurement during H-mode discharge, and the EFIT reconstruction showing strike points and the probe locations at the divertor region.

IV. CONCLUSIONS

According to the previous experimental results, high temperature baking (200℃) is quite effective to expedite the removal of water on the graphite PFCs. Consequently, all graphite tile of the PFCs were baked to 200℃ in maximum surface temperature. After PFCs baking, the VV pressure is decreased from 1.35 E-7 to 7.73 E-8 mbar and the partial pressure of mass 18 amu (water) is decreased from 2.5 E-8 to 1.5 E-8 mbar. Moreover, the partial pressure measurements showed that there was no nitrogen leakage in the PFC B&C lines, which satisfactorily meets the most important requirement in the PFCs system. KSTAR achieved H-mode in 2010 campaign. During the H-mode discharge, temperature of divertors is increased where the plasma is touching. That is same as result of EFIT calculation and the particle flux from the plasma boundary to the Langmuir probe. The heat flux after L-and H-mode is approximately 10kW/m^2 according to the increase of tile temperature.

ACKNOWLEDGMENT

This work is supported by Ministry of Education, Science and Technology under KSTAR project.

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